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RESEARCH PAPER

OPTIMIZATION OF WATER DISTRIBUTION NETWORKS FOR SUPERVISORY CONTROL USING GENETIC ALGORITHM

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ABSTRACT
Water distributions systems use interconnected elements such as pipes, pumps, valves and reservoirs to convey treated water from one or more sources to consumers spread over a wide area. The optimal strategy of pumps and valves settings for the present time steps as well as those up to a selected operating horizon, taking into account the short term demand fluctuations, the electricity tariff structure and operational constraints such as delivery pressure, flow and velocity is computed so as to minimize the energy supply cost. The case study is the Laminga Water Treatment Plant and its water distribution network. The optimal control setting for the present time steps (in this case 24 hours) is implemented using EPANET 2.0 Software which tracks the flow, velocity and pressure of water in each pipe or valve of each node as well as the head of water in each reservoir. This results in an energy savings of 15.98% using Genetic Algorithm Software GEATBX 3.3.

KEYWORDS: Software, EPANET 2.0, Water distributions, Treatment Plant, pipes, pumps

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INTRODUCTION
Water distribution networks (WDN) serve to transport clean water treated from plants to individual consumers and usually represent a significant capital investment in the development of the urban environment. The purpose of the network is to deliver water to the demand nodes from the water treatment plant, reservoir or other source throughout the day and under varying demand conditions. The demands on a WDN fluctuate throughout the day. Peak demand occurs when people prepare to leave for work at around 7am until 9am and when industrial organizations begin work for the day. It is important that demands on the network at peak times are satisfied (Baker *et al*., 2006).

Water networks are generally composed of a large number of interconnected pipes, reservoirs, pumps, valves and other hydraulic elements which carry water to demand nodes from supply areas, with specific pressure levels to provide a good service to consumers.

Water Distribution Network is mainly designed considering a demand pattern, pressure limitations, velocity limitations, quality assurances and maintenance issues at minimum cost (Dragan, 1999). Planning for an adequate water supply continues to be a challenge as water demand and supply reliability continues to change. With increased urbanization and consumer demand, most water distribution systems and efficient scheduling of Pump operation have become increasingly complex (Ting – Chao *et al*., 2005).

Optimal control in water networks deals with the problem of generating control strategies ahead of time, to guarantee good service in the network, while achieving certain performance goals, which may include one of the following, according to the needs of a specific utility: minimization of supply and pumping cost, maximization of water quality, pressure regulation for leak prevention, etc. (Cembrano *et al*., 2000).

The development of operational models of water supply systems that enlighten decision makers also continues to be a challenge (Randall *et al*., 1997).Some of the challenges in the water industry in Nigeria and the world at large in which capital constraints and operational cost escalation in the provision of portable drinking water has made it a necessity to evaluate technical, economic and environmental parameters to reach optimal solution. The determination of the optimal selection of system component required techniques that can be employed to assist the decision-makers in finding the appropriate solution within the environment of all the possible solutions (solution space) (Vuuren, 2002).

Jos the plateau state capital in central Nigeria has been characterized with water scarcity. The city had its major treatment plant, the Laminga treatment plant built in 1972, and since then there has been no major expansion in the network being served by the plant. The growing population of the city has forced the plateau state water board into rationing water to consumers and this has led into high cost of potable water in the city.

The objective of this paper is to optimize the set values of the valves, Pump discharge, and pressure at the demand nodes in the water distribution network for supervisory control.

This paper is organized as follows. The studied water Distribution network is described in section 2. Section 3 provides the theoretical overview of optimization, genetic Algorithm and supervisory control techniques. Simulation results and discussions of the study are contained in section 4. Conclusions are in section 5.

LAMINGA WATER DISTRIBUTION NETWORK

The Laminga water treatment plantJos and its distribution network covers old airport Road. Yakubu Gowon Way, Murtala Mohammed way, Dogon Karfe, Giring, Abattoir, mobile Barrack, Air Force Barracks, Gold and Base, Gwarandok, Daku, Rikkos, Liberty Boulevard, Apata, Zaria Bye-pass, Tafawa Balewa street, University of Jos, etc. as shown in Figure.1

The Laminga water distribution network contains 50 nodes and 5500 major pipes: it also has two reservoirs, old eastern site reservoir – 9200m^3 and ministry of works yard reservoir- 5500m^2 there are five fixed speed pumps; two operate on 600m^3 / h, and three on 341m^3 /h which are used to pump water from the treatment plant to the reservoirs . Two pumps with the capacity of 341m^3 /h are to be used to pump water to the ministry of works reservoir, with one pump on standby, while pumping to the old eastern site reservoir is done with one pump of capacity 600m^3 / h, with one on standby. But in practice three of the pumps for Ministry of works and two for the Eastern site are all put into use because it is believed it will pump more water to meet water demand.

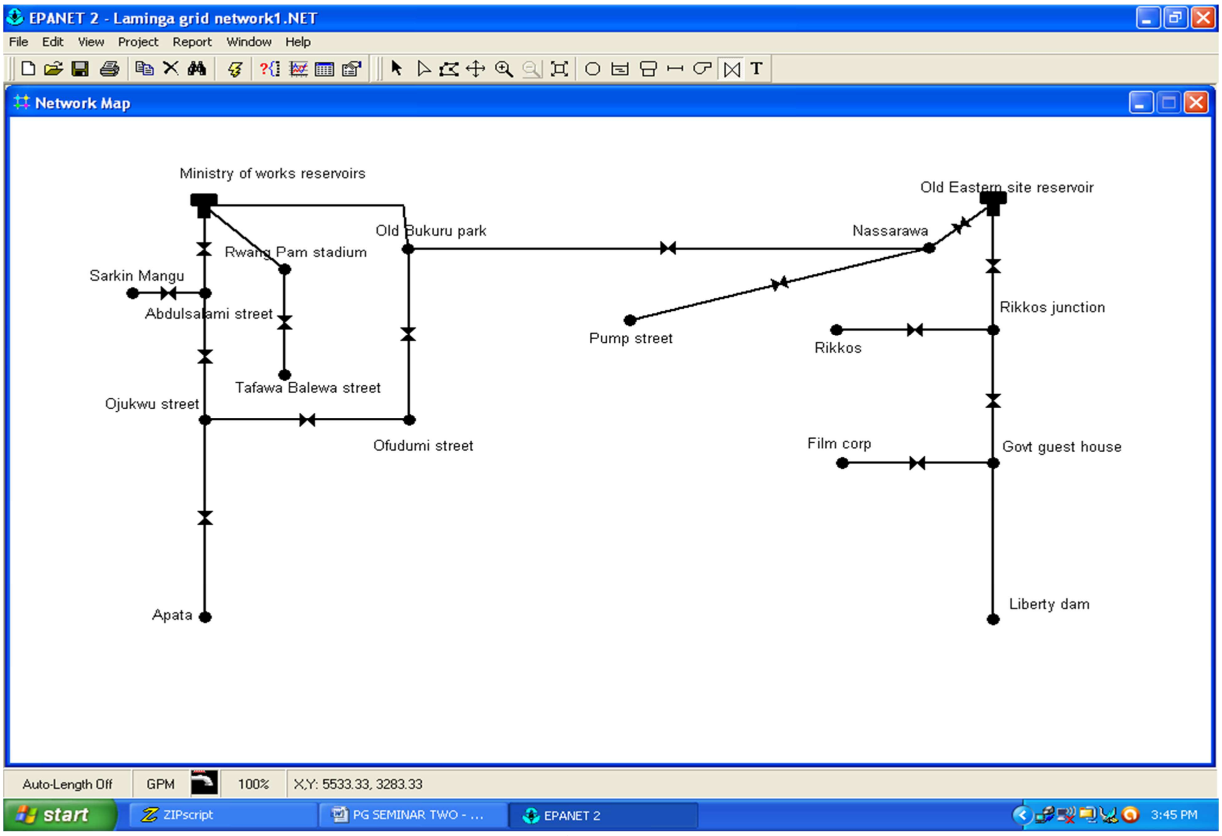

Figure 1: Selected demand nodes of the Laminga grid network.

OPTIMIZATION OF WATER DISTRIBUTION NETWORK

Optimization model

The objective of the model in this work is to develop a strategy for the optimal operation of pumps in water supply system operation. Total energy costs for pumping, which include energy charge, demand charge and other charges in the electricity rate, are to be minimized while satisfying water demands and physical constraints. The strategy must take into account the interaction between the pump controls resulting in limitations on pump discharges, maximum and minimum reservoir operating levels, and hydraulic relationship governing flows in water distribution network.
Let I, J and N be indices of reservoirs, pump stations and time steps, respectively. If there are IT reservoirs and JT pump stations operated during NT periods, the objective function can be stated as:

$$\text{Minimize Cost } = \sum_{J=i}^{JT} [G_u(.) + G_w(.)]$$

$$= \sum_{J=i}^{JT} \left[\sum_{K=1}^{KT} U_j\,[K].P\{X_j(K)\} \right] + w_j.\max_{K} \qquad \dots (1)$$

Where $G_u(.)$ = unit (or energy) charge in pump station J, $G_w(.)$ = demand (or capacity) charge in pump station, P ( ) = electrical power during time K, K ( ) = index of time interval, KT ( ) = total number of time intervals, U_j ( ) = unit (or energy) charge rate for pump station J during time, X (K) = X_j (K), discharge from pump station J during time K,

D (K) = Vector of DI (K), water demand at node associated with reservoir I during time K, F ( ) = function of pump discharge, reservoir volume, and demand satisfying conservation of flow, G_u ( ) = unit (or energy) charge in pump station J, G_w ( ) = demand (or capacity) charge in pump station J.

IT = total number of reservoirs in the system, JT = total number of pump stations in the system, K = index of time intervals, KT = total number of time intervals, P ( ) = electrical power during time K, **V** (K) = vector of V_I (K), volume of reservoir I at beginning of time K, V_I (K) = volume of upstream reservoir at the beginning of time K., U_j (K) = unit (or energy) charge rate for pump station J during time K, W_j= demand (or capacity) charge rate for pump station J and **X** (K) = vector of X_j (K), discharge from pump station J during time K.

Subscripts I = index of reservoirs, J = index of pump stations, U = unit (charge) and W = demand (charge)

*S*ubject to

1. Limitation of pump discharged

$$X_J(K) \le X_J(K) \le \overline{X_J}(K) \quad \forall J, K \qquad \dots (2)$$

2. Max- Min réservoir volumes

$$V_I(K) \le V_I(K) \le \overline{V}_I(K) \quad \forall I, K \qquad \dots (3)$$

3. Max- Min Pressure at the nodes.

$$P_{min} \le P \le P_{max} \qquad \dots (4)$$

4. Conservations of flow

$$V_i\ (K+I) = F\ [V_i\ (K), X\ (K), D\ (K)] \quad \forall\ I, K, \qquad \dots (5)$$

5. Known initial and target final reservoir volumes

$$V_I\ (1) = V_I^{\,initial} \qquad \dots (6)$$

$$V_I\,(KT+\ 1)\ V_I^{fina\ l} \forall, I \qquad \dots (7)$$

From the prior equations, the decision variable is the pump discharge $X_J(K)$. Eqs. (2)- (7) are model constraints. The reservoir volumes V_I *(K)*, is the state variable of the optimization model determined by the pump discharge and water demand from the conservation of flow in equation (5).

Concept of Genetic Algorithm

Genetic Algorithm was first proposed by John Holland in 1960, as a numerical optimization algorithm based on principles inspired from the genetic and evolution mechanisms observed in natural systems and populations of living beings. One of the features that distinguish Genetic Algorithms (GAs) from other conventional search methods is the characteristics to simultaneously deal with a population of points (solutions), thus leading to the disadvantage of requiring a relatively large number of functions evaluation. It is expected of the GA to be able to find an acceptable solution within a reasonable time when solving the optimization problem. Fundamentally, Gas differs in the following wats:

- GAs search from a population of candidates and does not process only one single solution; thus, they are resistant to being trapped in local optima.
- GAs use probabilistic transition rules and not deterministic rules.
- GAs exploits only the payoff information of the objective function to guide their search towards the global optimum. They do not depend on any additional information like existence of derivatives.
- GAs work with a coding of the problem parameters and not the parameters themselves.

Binary encoding GAs deal with binary strings, in which the number of bits of each string simulates the genes of an individual chromosome, and the number of individuals constitutes a population. Each parameter set is encoded into a series of a fixed length of string symbols, usually from the binary bits which are then concatenated into a complete

string called chromosome. Sub-strings of specified length are extracted successively from the concatenated string and are then decoded and mapped into the value in the corresponding search space. Generally, Gas implementation comprises three different phases: initial population generation, fitness evaluation and genetic operations. The processes involved in the implementation of conventional Gas are as described in the following steps.

STEP 1 : Start
STEP 2: Initialization and random generation of individuals in the population.
STEP 3: Fitness evaluation for each individual.
STEP 4: Test for convergence, if yes, go to STEP 7 else go to STEP 5.
STEP 5: Selection and mating of fit individuals, crossover and mutation.
STEP 6: Create a new population and apply elite preserving strategy and then go to STEP 3.
STEP 7: Stop

Steps 1 and 2 constitute the initial population generation, steps 3 and 4 constitute the fitness evaluation and steps 5 and 6 constitute the genetic operations

SIMULATION RESULTS AND DISCUSSIONS

The optimization of the water distribution network was carried out using the Genetic Algorithm (GA) software called Genetic and Evolutionary Algorithm Tool Box (GEATbx) for use with MAT LAB version 3.3 developed by Pohlheim (2006).The program written for the Optimization process was ran using a COMPAQ 615 Laptop with a RAM of 2.00GB.

The data used for the simulation are as shown in Tables 1 and 2

Table 1: Actual Reservoir Levels

Reservoir (Tanks)	**Capacity m^3**	
	Maximum	**Minimum**
Old Eastern site	9,200	1, 840
Ministry of Works	5, 500	1, 100

Table 2. Parameters of the Water Distribution Network used for EPANET simulation.

Demand Node		**Pipe Length , m**	**Pipe Diameter, m**
From	**To**		
X1	1	150	0.15
1	2	160	0.075
1	3	320	0.10
3	4	340	0.075
3	5	170	0.10
X1	6	3,450	0.30
6	7	5,201	0.20
X2	11	4,780	0.30
11	10	2,710	0.20
11	12	2,890	0.30
12	13	340	0.30
X2	14	5,780	0.20
14	15	2,450	0.20
X2	8	4,170	0.15
8	9	3,140	0.20
9	12	589	0.20

Optimization of Water Distribution Network
The results obtained from the optimization of the water distribution network are as shown in Table 3.

Table 3: The Best Objective Value Obtained, the GA Generation and the Computer time ran.

Parameter	**Value**
Maximum computer time	0.12 time minutes
Maximum computer time	1094.87
Generation	99

From the Optimization results obtained it is observed that every hour the plant consumes ₦1094.87, the objective value is equal to the amount charge per hour in the treatment plant operations, and this means for every 24 hours the plant operation will cost ₦26276.88 (twenty six thousand two hundred and seventy six naira eighty eight kobo).

Reservoir
There are two reservoirs connected to the water distribution network. The water pressure discharge of reservoir 1 within 24 hours is as shown in Figure 2. The graph of Fig. 3 shows a steady decrease in reservoir pressure from 1:00 hours to 22:00 hours, this is not unconnected with the fact that the reservoir is opened and allowed to discharge by gravity.

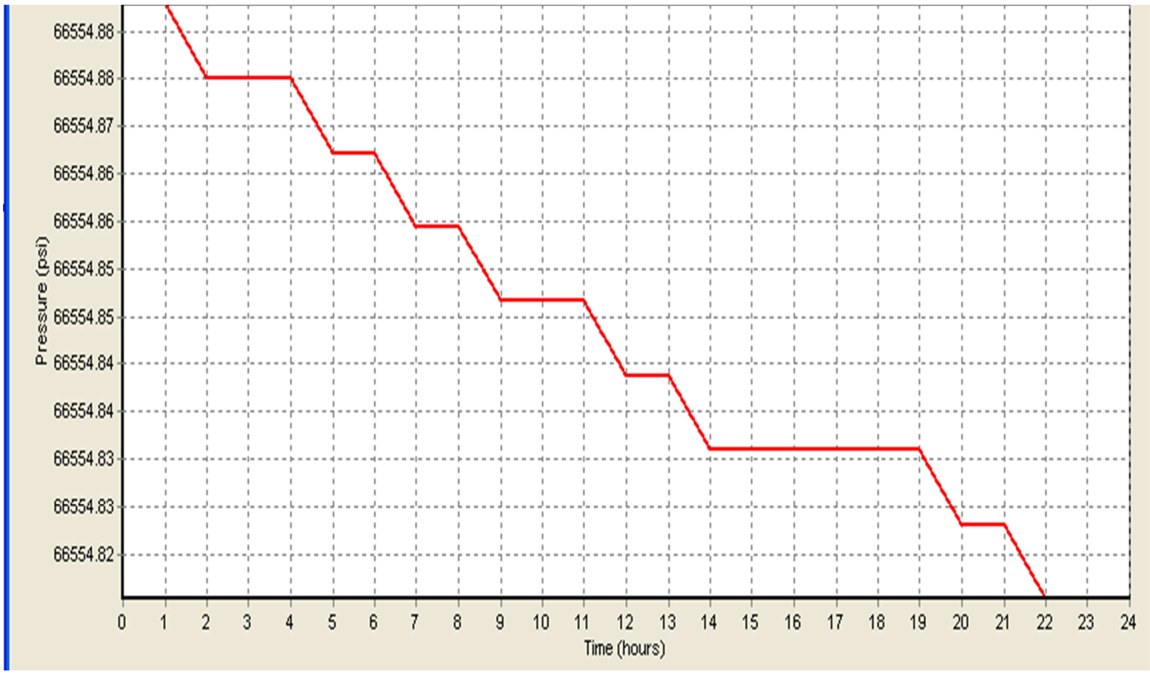

Figure 2: Water Pressure Discharge of Reservoir 1 within 24 Hours

Pumps
The simulated Laminga Network contains five Water pumps. The result of the output of pump 1 is shown in Figure 3.

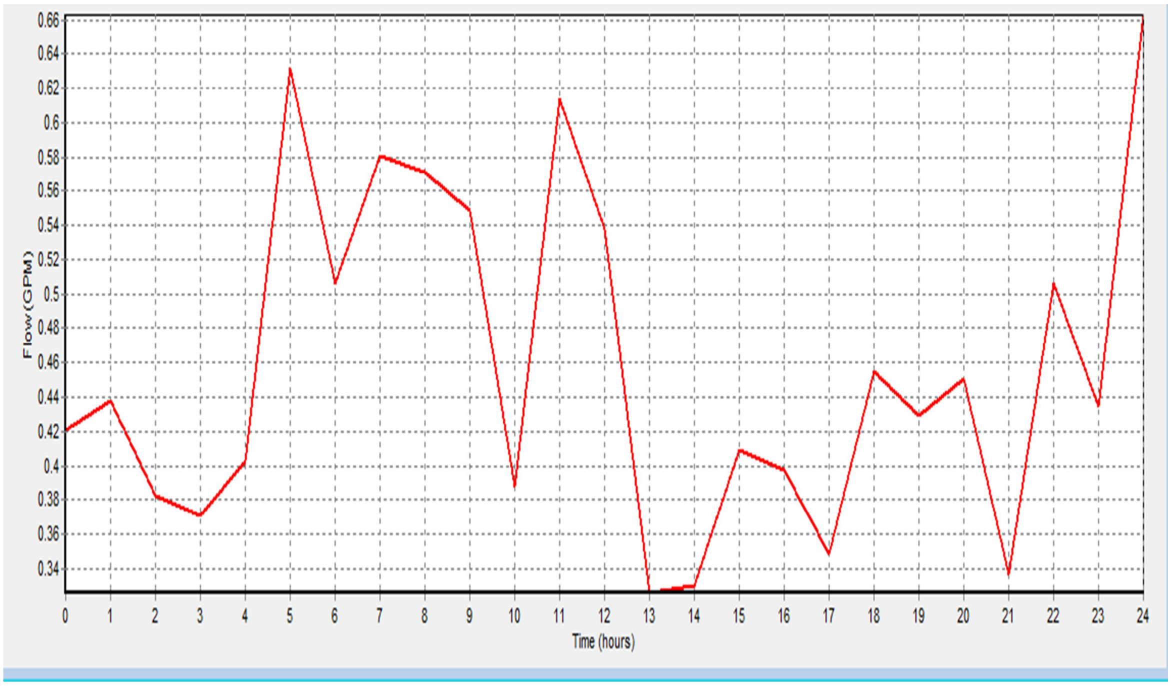

Figure 3: Volume of Water Pumped by Pump 1 for 24 Hours

Valves

The Laminga Treatment Plant network contains four Valves. The simulated output of Valve 1 is shown in Figure 4.

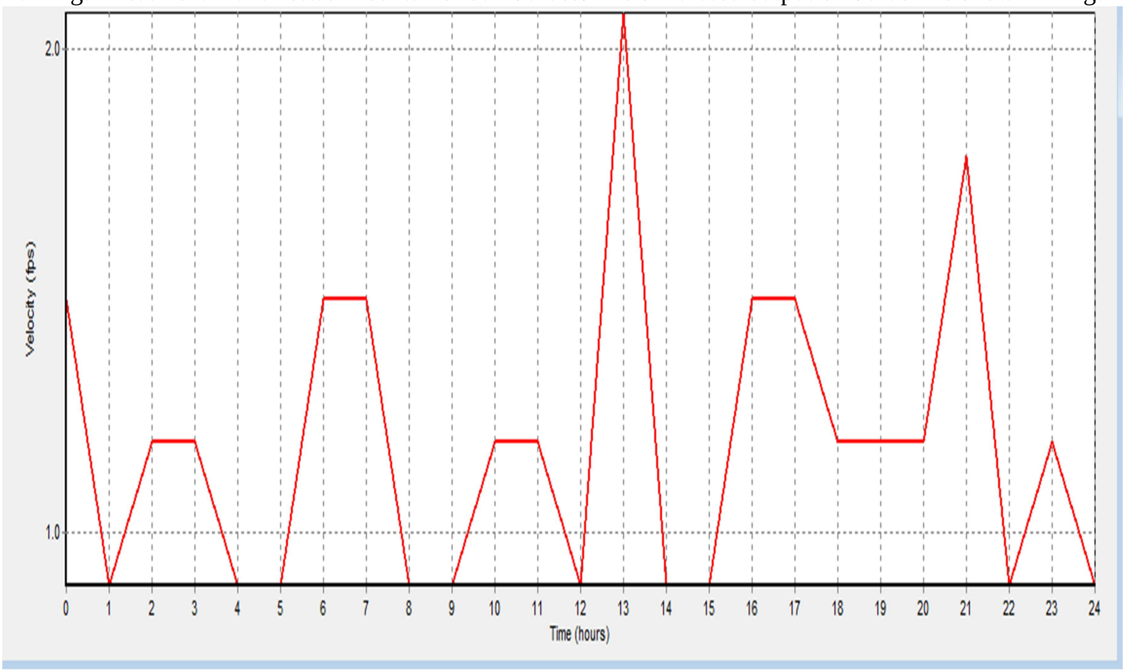

Figure 4: Water Velocity through Valve 1 for 24 Hours

Supervisory control

A program was written in Visual Basic, with the aid of Visual Studio to implement the supervisory control of water Distribution network. These modules consist of

- Logging in (username and password).
- Interface for activation and deactivation of valves.
- Interface demand node for activation and deactivation of pumps.

To access the interface as indicated Rikkos junction (node 1) was activated, control pumps 1 &2 were activated to allow water to be pumped into the network. The water flow and pressure for the Rikkos junction were visualized for various pump combination. The pumps and the Active water demand node were then shut down. The demonstration showed that the entire treatment plant process could be done and monitored at the computer terminal as expected of a SCADA.

CONCLUSION

The Best Objective value of ₦1094.87 per day (24hours) was obtained at iteration of 99 with a maximum computer speed of 0.12cpu minutes. Satisfactory results were obtained from the reservoirs, pumps and valves operations in which the water distribution network hydraulic parameters are within acceptable limits despite water demand at the distribution nodes. The Optimized water distribution network gave a total of 15.98% savings on Energy Cost, translating into ₦1, 373,858.00 (one million three hundred and seventy three thousand eight hundred and fifty eight naira). Simulated computer software with the aid of Visual Basic studio was used for supervisory control to monitor and control the water distribution in the network. The Practical application in the plant will cut down the cost of Water production and even to a large extend optimal operation of the water distribution networks solving the perennial problem of water scarcity.

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